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Gasifier selection, design and gasification of oil palm fronds with preheated and unheated gasifying air

Fiseha M. Guangul [a,*], Shaharin A. Sulaiman [a], Anita Ramli [b]

[a] Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia
[b] Department of Fundamental and Applied Sciences, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

HIGHLIGHTS

- ▶ A novel laboratory-scale single throat downdraft gasifier was developed.
- ▶ An air and steam inlet height adjustment mechanism was incorporated in the gasifier.
- ▶ Preheating the gasifying air improved the percentage of combustible gases.
- ▶ The syngas of oil palm fronds was comparable with that from other biomass feedstock.

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ABSTRACT

Oil palm frond biomass is abundantly available in Malaysia, but underutilized. In this study, gasifiers were evaluated based on the available literature data and downdraft gasifiers were found to be the best option for the study of oil palm fronds gasification. A downdraft gasifier was constructed with a novel height adjustment mechanism for changing the position of gasifying air and steam inlet. The oil palm fronds gasification results showed that preheating the gasifying air improved the volumetric percentage of H_2 from 8.47% to 10.53%, CO from 22.87% to 24.94%, CH_4 from 2.02% to 2.03%, and higher heating value from 4.66 to 5.31 MJ/Nm^3 of the syngas. In general, the results of the current study demonstrated that oil palm fronds can be used as an alternative energy source in the energy diversification plan of Malaysia through gasification, along with, the resulting syngas quality can be improved by preheating the gasifying air.

1. Introduction

The oil palm waste generated in Malaysia could provide 82.21% of the nation's total energy obtainable from biomass waste. The contribution of oil palm fronds (OPFs) generated from pruning and re-plantation constituted 46.71% (97 million tons per year) of the total oil palm waste on a wet basis. In terms of energy content, the contribution of OPF was about 43.16% (405.1×10^6 GJ) (CBBR, 2010; Shuit et al., 2009; Wahid, 2010). The pruning of OPF is carried out during harvesting of fruit bunches. Harvesting is done throughout the year and each oil palm tree is visited in 2-week intervals for a lifespan of about 25 years (Yacob, 2012; Yusoff, 2006).

Some efforts have been made to use fronds for the production of pulp and animal roughage and it is possible to use OPF and its ash as adsorbent for toxic gas and heavy metals; however, most fronds are still dumped at the plantation where some of the biomass serves in preventing soil erosion and promoting soil conservation (Hassan et al., 1996; Shuit et al., 2009; Yusoff, 2006). Hence, there is an opportunity to use this biomass waste for energy generation. Gasification is an option for energy generation by utilizing the biomass waste obtained from oil palm fronds (Sumathi et al., 2008).

Gasifiers are classified into three major categories depending on the solid–gas contact mode: (1) fixed or moving bed, (2) fluidized bed, and (3) entrained flow gasifiers. Each category has sub-classes. The gasifier design determines the application range. Fixed or moving bed gasifiers are applicable for smaller units within the range of 10–10,000 kW, fluidized-bed are more appropriate for intermediate units within the range of 5–100 MW, and entrained-flow gasifiers are used for large-capacity units above 50 MW (Basu, 2010).

Fixed bed gasifiers are the simplest gasifiers and are more suitable gasifiers for small-scale applications (Hsi et al., 2008; Reed and Das, 1988). In fixed bed gasifiers, the feedstock moves downward by gravity, and therefore, the bulk density of the feedstock has to be high enough for continuous downward flow during the gasification process. Hence, fixed bed gasifiers are more suitable

* Corresponding author. Tel.: +60 12 501 5843; fax: +60 5 365 6461.
E-mail address: fiseham2002@yahoo.com (F.M. Guangul).

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for feedstock with sufficient bulk density. Fixed bed gasifiers are classified into downdraft, updraft and crossdraft gasifiers depending on the gas flow direction (Rajvanshi, 1986).

Updraft gasifiers are simple counter-current types of gasifiers widely used for non-volatile fuels such as coal and charcoal (Reed and Das, 1988; Kythavone, 2007). The air intake is from the bottom and the gas outlet is from the top as shown in Fig. 1(a). Downdraft gasifiers are commonly developed to convert highly volatile fuels with a low amount of tar. For this reason the syngas produced from downdraft gasifiers can be used directly in internal combustion engines (Hsi et al., 2008; Lv et al., 2007; Reed and Das, 1988; Sheth and Babu, 2009). In downdraft gasifiers, biomass is fed from the top and air is introduced above the reduction zone. The air flows downward and reacts with the biomass hot bed and syngas exits at the bottom as shown in Fig. 1(b). Downdraft gasifiers are categorized into throated and stratified gasifiers depending on the design of the internal chamber. Throated gasifiers have the advantages of improving syngas quality, and reducing the tar amount since tar cracking would have occurred at the throat area with elevated zonal temperature (Basu, 2010; Koukouzas et al., 2008; Rathod et al., 2003). In crossdraft gasifiers, the air enters at high speed through a single nozzle which induces substantial circulation, and flows across the bed of fuel and char as shown in Fig. 1(c) (Reed and Das, 1988).

Fluidized bed gasifiers, shown in Fig. 1(d), are favorable for higher energy demand and smaller particle sizes (Reed and Das, 1988). In a typical bubbling or circulating types of fluidized bed gasifiers, air enters from the bottom, while the fuel is supplied either from the side or top (Basu, 2010). Entrained flow gasifiers are characterized by fuel particles dragged along with the gas stream as shown in Fig. 1(e). In an entrained flow gasifiers, the residence time is short (typically 1 s), process temperature is high

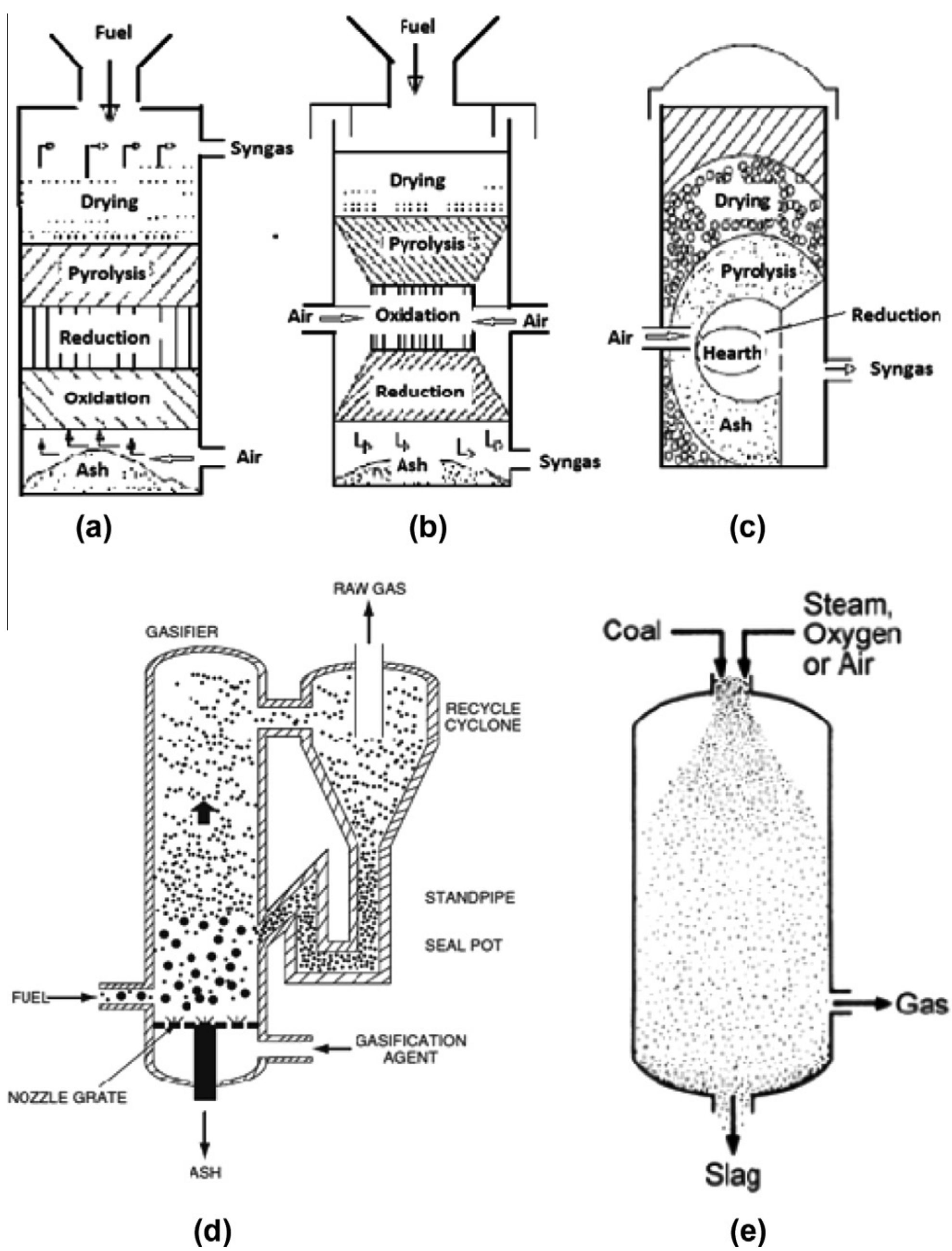

Fig. 1. Types of gasifiers (a) updraft, (b) downdraft, (c) cross-draft, (d) fluidized, and (e) entrained flow gasifiers (Chopra and Jain, 2007; Higman and Burgt, 2008; Reed and Das, 1988).

(typically 1300–1500 °C) and the fuel particle size is smaller (typically less than 100 μm). Furthermore, entrained flow gasifiers often operate under higher pressure (typically 20–50 bar) and with pure oxygen (Van der Drift et al., 2004).

In the current work, the effects of preheated and unheated air as a gasifying medium on the composition of syngas produced and the process performance of oil palm fronds gasification were studied. A downdraft gasifier was selected and fabricated with a novel height adjustment mechanism which enables the change of the air and steam inlet. Concentric pipes were used to achieve uniform distribution of the gasifying medium such that air flows through the external pipe and steam flows through the internal pipe.

2. Methods

2.1. Feedstock material and characterization

Freshly pruned oil palm fronds were collected at the Felcra classic oil palm plantation in Bota Kanan, Perak, Malaysia. Leaves were shredded and the petioles were chopped to a maximum of 25 mm in length. The chopped feedstock was air-dried over a period of 20 days to an average moisture content of 16% on a dry basis. Proximate analysis was carried out to determine the moisture content, volatile matter, ash and fixed carbon using a Pyris 1 TGA analyzer (PerkinElmer, USA). For ultimate analysis, a Leco CHNS-932 analyzer (Leco Corporation, USA) was used and carbon, hydrogen, nitrogen and sulfur content were determined. For calorific value measurements, a C5000 IKA bomb calorimeter (Cole-Parmer, USA) was used and gross calorific value was determined (Table 1).

2.2. Selection and design of the gasifier

2.2.1. Selection criteria

Seven criteria, namely cost of fabrication, ease of operation, tar content, cold gas efficiency, lower heating value (LHV), feedstock elasticity, and application versatility of syngas were considered for the gasifier selection. In the selection process, entrained flow gasifiers were excluded since they are not suitable for lower outputs. The criteria were weighted out of five, and the gasifiers were compared with each other on each criterion. The weights of the criteria were determined based on the importance to the objectives of the study, and on the limitations of resources to fabricate the gasifier. In the qualitative evaluation, the gasifiers were ranked as poor, fair, good, very good and excellent against each criterion, and score values of 1, 2, 3, 4 and 5 were assigned for the ranks, respectively (Table 2) (Abeyasekera, 2005; Belgiorno et al., 2003). The score values for each gasifier were assigned based on the qualitative information obtained from the literature.

Table 1
Basic characteristics of the oil palm fronds feedstock.

Proximate analysis (% dry basis)	
Volatile matter	83.5
Fixed carbon	15.2
Ash	1.3
Ultimate analysis (% dry basis)	
Carbon	44.58
Hydrogen	4.53
Oxygen	48.80
Nitrogen	0.71
Sulfur	0.07
Higher heating value (HHV)	17.28 MJ/kg
Moisture content (% dry basis)	16

2.2.2. Evaluation of gasifiers

Cost of manufacturing is related to fabrication complexity and materials used, while ease of operation is the easiness to handle the gasifier during gasification process. Thus, in both cases fixed bed gasifiers are cheaper to manufacture and easier to operation (Reed and Das, 1988; Kythavone, 2007). Downdraft gasifiers are relatively complex as compared to updraft and crossdraft gasifiers since the gas flow needs to be redirected at the outlet in order to minimize the exit of particulates and ash with the gas. Fluidized bed gasifiers are more complex and expensive than fixed bed gasifiers. Therefore, updraft and cross draft gasifiers are the cheapest followed by downdraft gasifiers, while fluidized bed gasifiers are the most expensive and complicated ones (Hsi et al., 2008; Koukouzas et al., 2008; Reed and Das, 1988).

Tar generation of downdraft gasifiers is lower than that of fluidized bed gasifiers. Updraft gasifiers have the highest tar production due to the discharge of un-combusted pyrolysis gas with the syngas. Crossdraft gasifiers are also poor in tar cracking (Basu, 2010; Belgiorno et al., 2003; Chopra and Jain, 2007; Koukouzas et al., 2008; Rajvanshi, 1986 Reed and Das, 1988; Kythavone, 2007). With regard to cold gas efficiency, updraft gasifiers are the most efficient followed by downdraft and fluidized bed gasifiers, while crossdraft gasifiers are the least efficient (Basu, 2010; Belgiorno et al., 2003; Chopra and Jain, 2007).

The LHV obtained from fluidized bed gasifiers are higher than those of moving bed gasifiers. Among moving bed gasifiers, updraft gasifiers have the highest LHV, followed by downdraft gasifiers, and cross draft gasifiers (Basu, 2010; Kythavone, 2007). With regard to feedstock versatility, fuels with a high moisture content (up to 60% on wet basis) can be used for gasification in updraft gasifiers. Furthermore, this type of gasifiers can also process a wide range of feedstock particle sizes (Reed and Das, 1988; Kythavone, 2007). Crossdraft gasifiers have the lowest tolerance for fuels with a higher moisture content as well as bigger particle sizes. Fluidized bed gasifiers need smaller particle sizes as compared to fixed bed gasifiers. The tolerance for feedstock moisture content is

Table 2
Gasifier selection criteria and weighted score values.

Sr. No.	Selection criteria	Relative weight (out of 5)	Score (out of 5)				Weighted score			
			U	D	C	F	U	D	C	F
1	Cost	5	5	4	5	1	25	20	25	5
2	Ease of operation	3	5	4	5	1	15	12	15	3
3	Tar content	5	1	5	4	3	5	25	20	15
4	Cold gas efficiency	5	5	3	1	3	25	15	5	15
5	LHV	5	3	3	1	5	15	15	5	25
6	Feedstock elasticity (moisture and size)	3	5	4	3	1	15	12	9	3
7	Application versatility	5	1	5	3	3	5	25	15	15
8	Total						105	124	94	81

U, updraft; D, downdraft; C, crossdraft; F, fluidized bed.
Score values: 1, poor; 2, fair, 3, good; 4, V. good; 5, excellent.

comparable with that of downdraft gasifiers (Basu, 2010; Belgiorno et al., 2003; Higman and Burgt, 2008; Rajvanshi, 1986). Therefore, the overall score of fluidized bed gasifiers are the lowest followed by crossdraft gasifiers, and updraft gasifiers are the highest followed by downdraft gasifiers.

The applicability of the resulting syngas was evaluated from the perspective of direct application (without cleaning) or with minimal cleaning cost. Since the amount of tar, particles and condensate are high in updraft gasifiers, the raw syngas can only be used for thermal applications. An intensive cleaning is required for engine applications and hence updraft gasifiers are the least suitable to use directly for different applications. The syngas produced using downdraft gasifiers can be used directly for thermal and engine applications (Olgun et al., 2010). Crossdraft and fluidized bed gasifiers need minimal cleaning of the syngas as compared to updraft gasifiers (Basu, 2010).

Table 2 shows the quantitative values of different gasifiers derived from the qualitative evaluations. The weighted scores were determined by multiplying the criteria weight with the score values. Finally, the evaluation was done by comparing the total weighted scores of the gasifiers. As shown in Table 2, downdraft gasifiers had the highest score of 124 and hence, downdraft gasifier was selected for the study of OPF gasification. In the design and development of the gasifier, a single throat was incorporated in the chamber as the resulting syngas quality and tar cracking capability are better than those of stratified types (Basu, 2010; Koukouzas et al., 2008; Rathod et al., 2003).

2.2.3. Determination of gasifier size

The internal diameter of the gasifier was determined by the required power output, while the height was determined by the required time for one batch operation. Eqs. (1)–(3) were used for the determination of the internal diameter, height and output power of the gasifier (Belonio, 2005).

The diameter (D) can be determined as:

$$D = \left(\frac{1.27 \times \mathrm{FCR}}{\mathrm{SGR}}\right)^{0.5} (\mathrm{m}) \tag{1}$$

where, FCR is the fuel consumption rate (kg/h), and SGR is the specific gasification rate (kg/h m^2). The height (H) can be determined as:

$$H = \frac{\mathrm{SGR} \times t}{\rho} (\mathrm{m}) \tag{2}$$

where, t is operation time (h), and ρ is the feedstock bulk density (kg/m^3). The power output (P_o) can be determined as:

$$P_o = \frac{\mathrm{FCR} \times \mathrm{HHV} \times \eta}{3.6} (\mathrm{kW}) \tag{3}$$

where, HHV is the higher heating value of the feedstock (MJ/kg) and η is the efficiency of the gasifier.

Therefore, the diameter, height and power output of the gasifier were determined to be 300 mm, 1100 mm and 33.6 kW, respectively using the values shown in Table 3. To minimize the problem of bridging, the throat diameter is recommended to be at least five times larger than the particle size of the feedstock (Rathod et al., 2003; Venselaar, 1982). Hence, the diameter of the throat was determined as 150 mm since the maximum chopped particle size of the feedstock was 25 mm length.

2.2.4. Amount of air needed

The amount of air flow rate was determined based on fuel consumption rate (FCR), stoichiometric air, and the recommended equivalence ratio (ε) by using Eqs. (4) and (5) (Belonio, 2005; Moran and Shapiro, 2004). The stoichiometric air (SA) can be determined as:

Table 3
Input data for the design of the gasifier.

Description	Value	Remark/reference
Feedstock particle size	$\leqslant$25 mm	Chopped size
Chemical composition	$CH_{1.21}O_{0.82}$	Determined from ultimate analysis result
Higher heating value (HHV)	17.28 MJ/kg	Measured
Average moisture content	16%	Measured
Bulk density	160 kg/m^3	Measured
Operation time	1 h	Required running time
Equivalent ratio (ε)	0.3	Basu (2010)
Gasification efficiency (η)	70%	Kythavone (2007)
Specific gasification rate (SGR)	150 kg/h m^2	Kythavone (2007)
Fuel consumption rate (FCR)	10 kg/h	Amount of fuel for 1 h operation
Density of air (ρ_a)	1.18 kg/m^3	Measured

$$\mathrm{SA} = \overline{\mathrm{AF}}\left(\frac{M_{\mathrm{air}}}{M_{\mathrm{fuel}}}\right) \tag{4}$$

where, $\overline{\mathrm{AF}}$ is the air to fuel ratio on molar basis, M_{air} and M_{fuel} are the molecular weight of air and fuel, respectively. Therefore, the stoichiometric air was determined to be 6.26 kg of air per kg of fuel. The air flow rate (AFR) can be determined as:

$$\mathrm{AFR} = \frac{\varepsilon \times \mathrm{FCR} \times \mathrm{AS}}{\rho_a} (\mathrm{Nm^3/h}) \tag{5}$$

where, ε is the equivalent ratio, FCR is the fuel consumption rate, and ρ_a is the air density. Therefore, the air flow rate was determined to be 15.9 Nm^3/h.

2.2.5. Nozzle design

To obtain uniform distribution of air in the cross-section of the gasifier chamber, an optimal air velocity and proper air distribution are essential. The size of the nozzle (A) can be determined as:

$$A = \frac{\mathrm{AFR}}{v} \times \frac{10^3}{3.6} (\mathrm{mm^2}) \tag{6}$$

where, AFR is the air flow rate (Nm^3/h), and v is the inlet velocity of the air (m/s) (Rudakova, 2009).

Assuming air velocity and number of nozzles to be 8 m/s and 4, respectively (Rudakova, 2009), the diameter of each nozzle was determined to be 13 mm. The four nozzles are located at 90° angles on the diameter of air inlet pipe. The inlet nozzles of the steam were designed in a similar manner. Concentric pipes are used for the inlet of air and steam as shown in Figs. 2 and 3. The air passes through the outer pipe and the steam passes through the inner pipe. To obtain uniform distribution of air and steam, the inlet position of the air and steam were located to be at the center of the throat diameter. In addition, a mechanism was incorporated in the design to allow varying the height of the inlet position of air and steam up to 120 mm vertically. Hence, this facility enables to study the effects of varying inlet position of air and steam on the gasification process.

2.2.6. Fabrication of the gasifier

The gasifier was fabricated in a local workshop according to the design. The internal lining and insulation were constructed from 50 mm thickness refractory cement. The gasifier has two openings on the top for feeding of the fuel. The grate and ash box can be dismantled easily for maintenance and cleaning purpose as shown in Fig. 2.

Fig. 2. Completed gasifier and semi-finished parts.

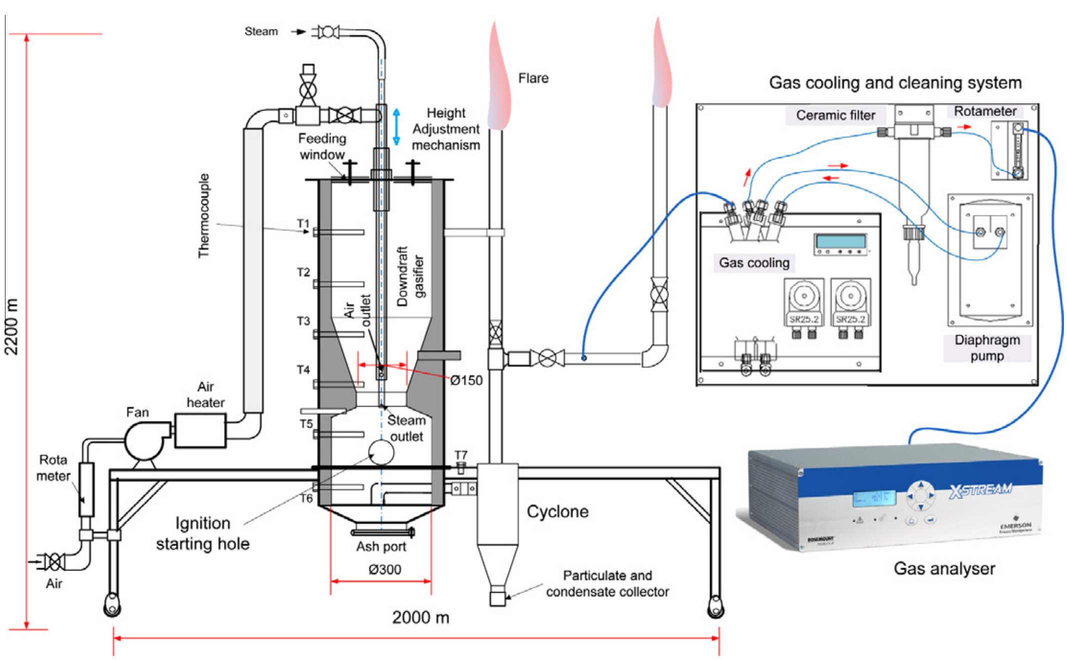

Fig. 3. Experimental set-up design.

2.3. Experimental set-up

The experimental set-up consists of the components shown in Fig. 3. To measure the temperature at different positions, six thermocouples were fixed on the gasifier with a 215-mm gap along the height. In addition, one thermocouple was fixed at the outlet pipe to measure the syngas temperature after it leaves the gasifier. The sample gas cleaning system consists of the electric gas cooler, diaphragm pump, 4-μm ceramic filter, and rotameter with a valve for gas flow control as shown in Fig. 3. To measure the volume percentage of the gas, X-Stream X2GP (Emerson, Germany) gas analyzer was used.

2.4. Experimental procedure

Before starting the gasification process, the thermocouples were fixed and the gasifier was filled with 9 kg of OPF feedstock. When unheated air was used as a gasifying medium, ignition was started using scrap paper and an ignition lighter through the ignition starting hole. After ignition, the hole was closed and air was supplied by the blower through the air inlet pipe. The air flow rate was adjusted and controlled using a rotameter and valve. When preheated air was used at 350 °C, the feedstock self-ignited. The temperature in the gasifier was measured using seven thermocouples and recorded using a data logger and computer. For gas composition measurements, the sample gas was tapped from the syngas outlet pipe and pumped to the gas cooling and cleaning system before it was supplied to the gas analyzer. Thus, the composition of the gas was recorded on the gas analyzer display. The remaining syngas was flared at the flare points. Char and ash were collected from the ash box and on the grate after the process was stopped and the gasifier had cooled. Weight measurements of the ash and char were taken using an Ohaus precision standard weighing balance.

3. Results and discussion

3.1. Preliminary experiments for the determination of the range of gasifying air flow rate

To investigate the practical range of air flow rate needed for the gasification process, a preliminary experiment was conducted by varying the flow rate of air and then the nature of the flare was investigated. In the experiment using unheated gasifying air, flare was observed when the flow rate exceeded 200 L/min. The flare strength and stability increased as the air flow rate increased to 400 L/min. In addition, at 400 L/min air flow rate, a flare temperature of 350 °C was recorded at the flare point. At the same flow rate, the oxidation zone temperature reached 985 °C. The nature of the flare became unstable when the air flow rate exceeded 500 L/min, likely due to an increased amount of CO_2 and N_2. CO_2 could be increased due to the increased equivalence ratio as a result of a high amount of air in the process which favored oxidation reactions. In addition, the increased flow rate of air caused an increase in the percentage composition of N_2 in the syngas.

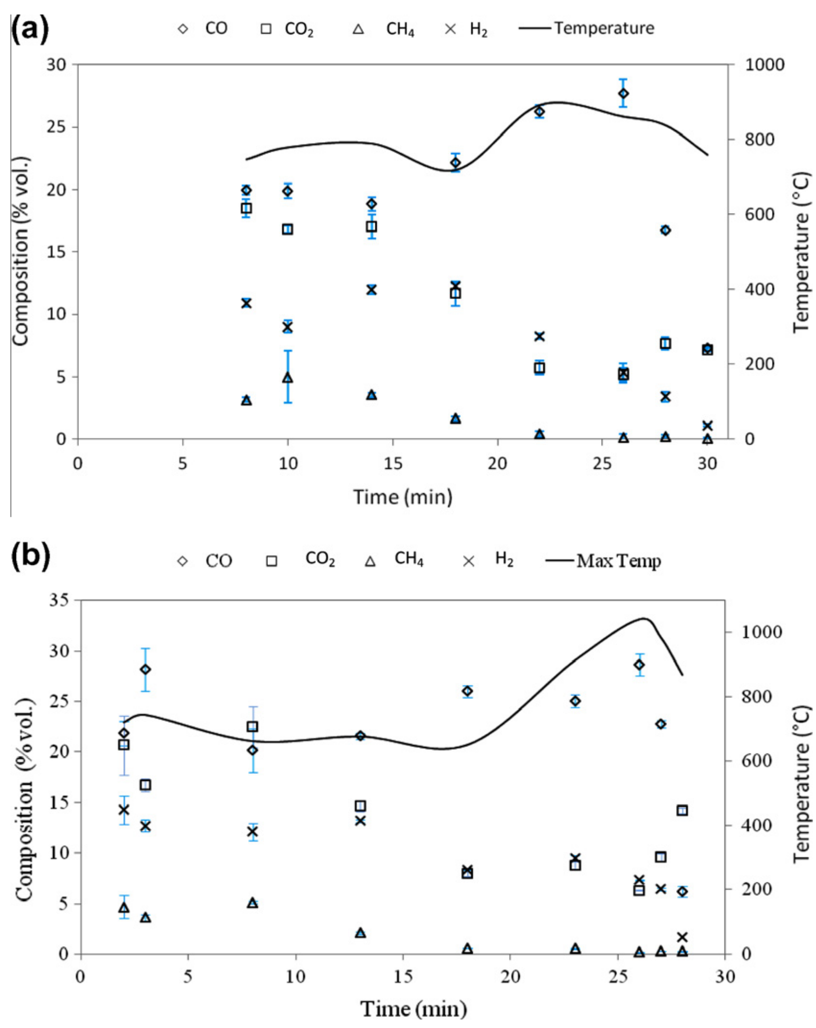

Fig. 4. Syngas composition and oxidation zone temperature over time (a) for unheated air and (b) for air preheated at 350°.

Consequently, the percentage of combustible gases (CO, CH_4, H_2) in the syngas decreased, causing the flare to become unstable and weak.

3.2. Effects of preheating the gasifying air on the outputs of the process

To investigate the effects of preheating the gasifying air, experiments were conducted using preheated and unheated air at 400 L/min flow rate. In the first experiment the air was supplied without preheating at ambient temperature. After 8 min from start of the gasification, the process reached at steady state condition and a stable flare was obtained. The gas composition data recording was also started after 8 min of the process. The average composition of the syngas and the standard errors of the mean values of three results which were taken in 20 s interval are shown in Fig. 4(a) and (b). The results showed that the volume of hydrogen started to drop after 20 min from the start of the gasification process, whereas carbon monoxide increased after 14 min. The volume of CH_4 also started to decrease after 14 min and dropped below 1% after 22 min.

In batch type and fixed bed gasifiers, the amount of feedstock, moisture content and volatile matter in the feedstock decrease as the gasification process time increases. Particularly, in small fixed bed gasifiers, the relative time of the steady state gasification from the total gasification time is shorter than that of bigger gasifiers. Therefore, it would be difficult to achieve a stable and uniform syngas composition for downstream applications for a longer time throughout the process. As shown in Fig. 4(a), the amount of combustible gases in the syngas varied as gasification time increased. The main reasons for the drop in H_2 and CH_4 could be the depletion of moisture and pyrolysis gas in the feedstock. Narvaez et al. (1996) reported an increasing H_2 content from 5% to 9% during pine sawdust gasification when the moisture content increased from 10% to 25%. Lahijani and Zainal (2011) also argued that the higher H_2 value obtained from gasification of sawdust (14.6%) compared to empty fruit bunch (EFB) (7.8%) was due to the higher moisture content of sawdust. As a result of the moisture content reduction in the feedstock, steam and hydro-gasification reactions become slower. At the same time, the accumulation of char on the grate increased as the gasification time increased. Therefore, CO_2 formed by oxidation in the oxidation zone formed more CO when it was passing through the char bed accumulated on the grate. Hence, the amount of CO remained stable as compared to H_2 and CH_4 for a longer time. After 20 min, when the temperature increased, CO increased, possibly due to an increase in the Boudouard reaction as the gasification temperature exceeded 730 °C (Basu, 2010).

The result obtained with preheated gasifying air is shown in Fig. 4(b). The process reached at steady state and a stable flare was obtained after 3 min of gasification starting time. After 15 min, the amount of CH_4 and H_2 decreased. CH_4 dropped below 1% after 18 min and H_2 dropped below 2% at 28 min. The amount of CO remained stable until 23 min and increased when the gasification temperature increased at 26 min. The drop in H_2 and CH_4, and increase in CO were likely caused by the decreasing moisture content and volatile matter in the feedstock and increasing char accumulation on the grate. The comparison of the syngas composition obtained with and without preheating of the gasifying air is shown in Table 4. Also shown is the comparison of the composition of the current results with those from the literature. The performance of the process was also evaluated by determining HHV, dry gas yield, carbon conversion efficiency and gasification efficiency using the empirical formulas shown in Eq. (7) through (10) (Xiao et al., 2006). The HHV can be determined as:

$$\mathrm{HHV} = (\mathrm{H_2\%} \times 3.052 + \mathrm{CO\%} \times 30.18 + \mathrm{CH_4\%} \times 95) \times 0.0042(\mathrm{MJ/Nm^3}) \quad (7)$$

Table 4
Comparison of OPF results with literature results of different feedstock.

Feedstock type	HHV (MJ/kg)	Gasifying medium	Equivalent ratio	Average syngas composition (Vol.%)				Syngas HHV (MJ/Nm^3)	Gas yield (Nm^3/kg)	Carbon conversion efficiency (%)	Cold gas efficiency (%)	Source
				CO	CO_2	CH_4	H_2					
Oil palm fronds	17.28	Unheated air	0.27	22.78	11.81	2.02	8.47	4.66	1.91	74.4	51.5	Current result
		Preheated air	0.22	24.94	12.80	2.03	10.53	5.31	1.94	93.0	59.6	Current result
Wood chips	20.50	Ambient air	0.35	23.8	13.51	2.6	13.50	5.77	na	na	na	Olgun et al. (2010)
Pelletized bagasse, 6 mm	17.93	Ambient air	0.27–0.30	23.30	11.40	2.80	9.90	5.32	na	na	na	Erlich and Fransson (2011)
Pelletized wood, 6 mm	20.27	Ambient air	0.28–0.30	25.70	9.90	2.60	11.90	5.80	2.0–2.1	na	na	Erlich and Fransson (2011)
Pelletized EFB, 6 mm	18.05	Ambient air	0.23–0.37	17.00	14.50	1.90	13.50	4.63	1.8–2.1	na	na	Erlich and Fransson (2011)
Pelletized EFB, 8 mm	18.05	Ambient air	0.34–0.43	17.40	13.70	1.50	12.90	4.44	2.1–2.5	na	na	Erlich and Fransson (2011)
Residual eucalyptus wood	18.14	Ambient air	0.35	17.34	na	1.79	16.70	5.04	na	na	na	Martínez et al. (2011)

Na, not available.

The dry gas yield (Y) can be determined as:

$$Y = \frac{Q_a \times 0.79}{W_b(1 - X_{ash}) \times N_2\%} \ (\mathrm{Nm^3/kg}) \tag{8}$$

where, Q_a is the flow rate of air (Nm^3/h), W_b is the mass flow rate of feedstock (kg/h), X_{ash} is the ash content in the feedstock and N_2% is the volumetric percentage of N_2 in the dry syngas.

Carbon conversion efficiency, η_c (%), can be determined as:

$$\eta_c = \frac{Y(CO\% + CH_4\% + CO_2\%) \times 12}{22.4 \times C\%} \times 100\% \tag{9}$$

where, CO%, CH_4% and CO_2% are the volumetric compositions in the syngas, and C% is the carbon content of the feedstock by weight.

Cold gas efficiency, η (%), can be determined as:

$$\eta = \frac{H_g \times Y}{H_b} \times 100\% \tag{10}$$

where, H_g (MJ/Nm^3) and H_b (MJ/kg) are the heating value of syngas and biomass, respectively.

The results in Table 4 showed that preheating of the gasifying air improved the volume percentage of CO, CH_4 and H_2 from 22.78, 2.02 and 8.47 to 24.94, 2.03 and 10.53, respectively. HHV, dry gas yield, carbon conversion efficiency and gasification efficiency were also improved when preheated air was used. HHV was improved from 4.66 to 5.31 MJ/Nm^3, dry gas yield from 1.91 to 1.94 Nm^3/kg, carbon conversion efficiency from 74.4% to 93.0%, and gasification efficiency from 51.5% to 59.6%. Preheating of the gasifying air also reduced the time required to obtain a stable gasification process. In addition, the time to get a flare was reduced from 8 to 3 min after ignition. The amount of char and ash collected in the ash box and on the grate at the end of the gasification process using unheated and preheated air were 786 and 678 g, respectively.

Although pelletizing of biomass feedstock can improve the quality of the resulting syngas (Sokhansanj and Turhollow, 2004), the HHV of the syngas obtained from chopped OPF using unheated air was comparable with that obtained from pelletized empty fruit bunch (EFB) (Table 4); however, the HHV obtained from OPF syngas was lower than that obtained from woodchips, pelletized bagasse, pelletized wood, and eucalyptus wood residues. The difference in HHV of the syngas is possibly due to the difference in HHV of the feedstock. As the HHV of woodchips, pelletized bagasse, pelletized wood, and eucalyptus wood residuals were 20.5, 19.26, 20.27, and 18.14 MJ/kg, respectively, while the HHV of OPF was 17.28 MJ/kg. However, when preheated air was used as a gasifying medium the HHV of OPF syngas was better than that from eucalyptus wood residuals and comparable with that from pelletized bagasse. Since pelletizing of feedstock and using preheated air as a gasifying agent incur additional cost on the process, the choice of application of either or both techniques depend on the overall economics. Generally, the results obtained from gasification of OPF were in the acceptable range for biomass gasification.

4. Conclusions

Using a single throat downdraft gasifier, the syngas obtained from oil palm fronds gasification was comparable with that generated from other types of biomass wastes. Preheating the gasifying air was found to improve the syngas quality, gas yield, and carbon conversion and cold gas efficiencies. The syngas produced from oil palm fronds gasification with preheated air consists of 10.54% H_2, 24.94% CO and 2.03% CH_4 (vol/vol) with higher heating value of 5.31 MJ/Nm^3. Hence, oil palm fronds waste can be used as an alternative source of energy for Malaysia's energy diversification plan through gasification.

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